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Using PBN for Terminal and Extended Terminal operations

Navigation Performance Data Analysis and its Effect on Route Spacing

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***Abstract*—Radar track data was collected during one year from three major Air Navigation Service Providers in Europe, providing Air Traffic Control to the international airports of Paris Charles de Gaulle, Amsterdam Schiphol and London Heathrow. The data consisted of departure, arrival and approach transition instrument flight procedures. Using a custom built application and filtering process, tactical interventions from Air Traffic Control were removed from the dataset. The remaining dataset was used to compute cross-track deviations from the route centerline of the procedures, both along straight segments and in turns. For the turns the route centerline was defined by an average turn radius which was calculated for each turn in the procedure. These cross-track deviations were used to compute lateral navigation performance distributions for straight segments, turns and for different speed and turn angle categories. The general observation was that according to these computed performance distributions, the actual lateral navigation performance of the current fleet in Europe operating to the three major airports from which data was collected, is outstanding and far better than the required navigation performance defined in the ICAO standards. For example, the lateral track keeping accuracy along straight segments, for groundspeeds exceeding 350 knots, had a standard deviation of only 0.07NM. Subsets of data consisting of aircraft navigating without GNSS were also analyzed. Finally the performance distributions were injected in a Collision Risk Model to determine the required route spacing for a set of sample parallel route configurations in function of a target level of safety. It was concluded that, thanks to the excellent actual navigation performance, navigation performance is not the prevalent factor anymore in route spacing determination in a radar environment. Instead, radar separation minima and human factors such as the controller's screen resolution and ATC sector size are the more dominant elements for the determination of route spacing minima.**

Keywords - Performance Based Navigation, Route Spacing, Collision Risk Modeling, Navigation Performance

I. INTRODUCTION

Various European route spacing studies have been conducted over the past three decades. An overview of the route spacings from these studies is given in Figure 1 [1].

One characteristic of these studies is that they used historical navigation performance data to determine the lateral overlap probabilities. A well-known reference for this historical data is the EUROCONTROL report 216, "Navigational Accuracy of Aircraft Equipped with Advanced Navigation Systems – Final Report", June 1988 [2]. Until the beginning of 2015, nearly all EUROCONTROL Route Spacing CRM studies were based on data from this report. Some studies, especially the Advanced RNP [3] route spacing study, were complemented by real-time simulations during which the proposed route spacings were operationally evaluated and validated by controllers. Already it was found that besides the results obtained from Collision Risk Modeling, operational constraints such as controller workload and radar display resolution were important factors to take into account in the determination of route spacings [4].

Spacing between Parallel Routes	How spacing demonstrated	Airspace Applicable	Extra distance needed on turns	Nav Spec	Additional conditions (DOC ref)
16.5 NM	Comparative Analysis	En route between straight tracks only; same direction	YES	B-RNAV	As per generic safety assessment
18 NM	Comparative Analysis	En Route between straight tracks only; opposite direction	YES	B-RNAV	As per generic safety assessment
10 to 15 NM	ATC Intervention Studies	n/a	YES	B-RNAV	As per generic safety assessment
8-9 NM	CRM	En route between straight tracks only; same direction	YES	P-RNAV	As per generic safety assessment
7 NM (London-Paris)	CRM	En route between straight tracks only; same direction	YES	P-RNAV	As per generic safety assessment
7-8 NM	CRM	Terminal between straight tracks only; same direction	YES	P-RNAV	As per generic safety assessment
7 NM	CRM + 2 RTS	En route	NO	Advanced RNP (1 NM TSE)	As per generic safety assessment and RTS report
7 NM	CRM	Terminal	NO	Advanced RNP (1 NM TSE)	As per generic safety assessment
5 NM	2 x RTS	Terminal	NO	Advanced RNP (1 NM TSE)	As per generic safety assessment and RTS report
6 -7 NM	CRM	Terminal	NO	Advanced RNP (0.5 NM TSE)	As per generic safety assessment

Figure 1. Overview of past route spacing studies and resulting route spacings.

Another issue with these past studies is the nature as well as the age of the data used from [2]. This data was collected before 1988 in Karlsruhe and Maastricht upper airspace, excluding any terminal area. Most of the aircraft types and equipment from which the navigation performance was measured are currently no longer operating in European airspace (e.g. Tristar, DC10, Airbus 310) and pre-date the GNSS era. RNAV systems were exclusively based on automatic DME-DME updating of inertial sensors. An example of the navigation performance documented in [2] and used in previous CRM route spacing studies, is a lateral Total System Error (TSE) along a straight segment of a route of below 0.85NM with 95% probability and a TSE below 1.4NM with 99% probability. For the reasons mentioned above, it was decided that for the collision risk modeling undertaken in this work, new navigation performance data was needed.

II. NEW NAVIGATION DATA COLLECTION

A. Origin of the data

Data collection began at the start of 2014 and was provided to EUROCONTROL by 3 major European ANSPs: LVNL (Amsterdam Schiphol airport), NATS (London Heathrow airport) and DSNA (Paris Charles de Gaulle airport)[1]. Table I provides an overview of the number of procedures at the three airports for which data was collected, as well as the duration over which the data was collected.

TABLE I. DURATION AND AMOUNT OF DATA COLLECTED

	DSNA	LVNL	NATS
Duration	Jan-Dec 2014	April-Sept 2014	Jan-March 2014
No. of SIDs	35	22	4
No. of STARs	2	9	0
No. of Approach Transitions	7	7	0

B. Data filtering

To analyze the data, a tool was developed by EUROCONTROL navigation experts, in which the data can be loaded, visualized and processed. The recorded data is compared with the reference procedure which is coded in the tool. An example of the map in the tool is provided in Figure 2.

As the received data contained all the tracks recorded in the specified time period (including the tracks which deviated from the planned route due to ATC intervention), the data had to be filtered. A three-step process was created for the data filtering:

- Step 1: selection of the start and end segments of the reference route; this was done by visually determining route segments for which route adherence was generally acceptable. For example in Figure 2, this was the route segment from BANOX to PG510.
- Step 2: automatic filtering out all excessive deviations from the reference route between the defined start and end segments. Excessive deviations (radar vectors) were defined as deviations for which the cross-track error from the reference route exceeded a certain threshold.
- Step 3: Visual inspection of each remaining track, one by one.

[1] DSNA – Direction des Services de la Navigation Aérienne (France)
LVNL – Luchtverkeersleiding Nederland (The Netherlands)
NATS – National Air Traffic Services (United Kindom)

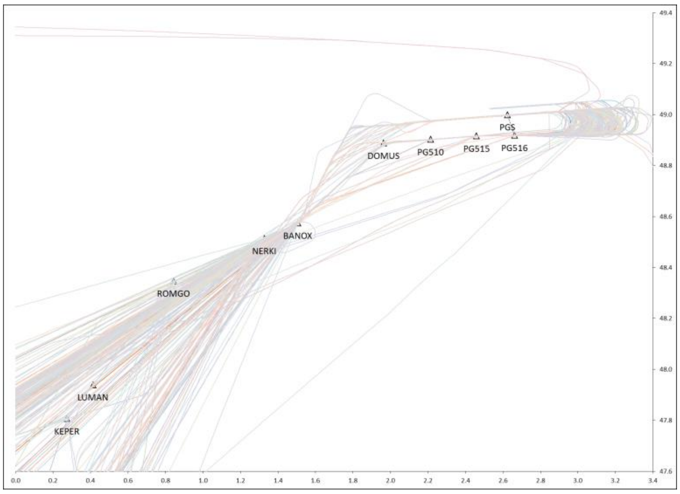


Figure 2. Tracks in EUROCONTROL navigation data analysis tool.

Figure 3 provides an example containing the same tracks as those in Figure 2 after they were processed by the automatic filter. The start and end points of the reference route were BANOX and PG510. The threshold for excessive deviations in the automatic filter was set to 1.3NM. Out of 250 tracks in Figure 2, 218 tracks remain in Figure 3. The 32 deleted tracks were all tracks that obviously were radar vectored to one of the waypoints after BANOX or to a right-hand downwind pattern. One remaining track which passed the automatic filtering but which was removed after visual inspection during Step 3, is indicated in red in Figure 3. The reason why it was removed was that although it was close to the route centerline of the reference procedure, the track had a typical shape which suggested radar vectoring.

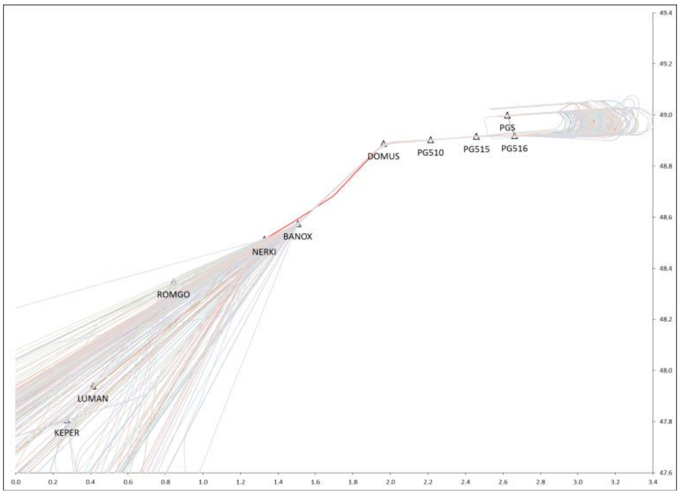


Figure 3. Remaining tracks in data analysis tool after Step 1 and 2 of the filtering process.

Figure 4 provides another example of a procedure (different than the procedure shown in Figure 2) whereby the displayed aircraft track obviously deviates from the route centerline. However in this case, the track was not removed from the dataset because the nature of the deviation is not clear. Probably the deviation was not due to radar vectoring.

In summary, due to lack of availability of ATC audio recordings for the whole dataset in combination with the huge volume of data, the data was filtered using a process involving automatic filtering and intensive visual inspection of each track, to remove tactical interventions from the dataset. The quality of the filtering process was assessed as explained in the next paragraph.

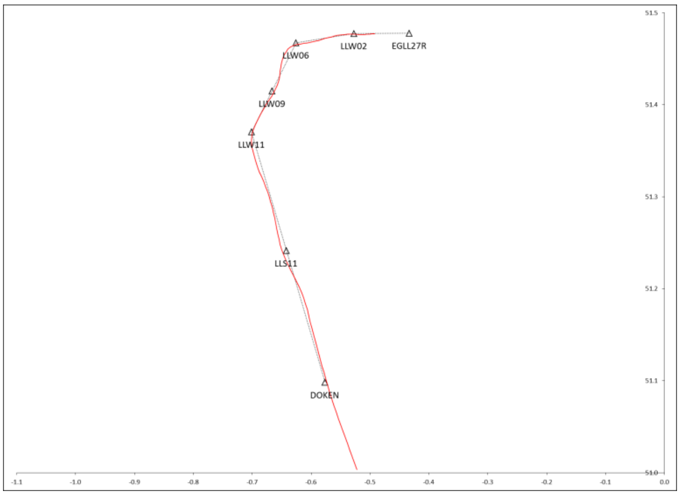


Figure 4. Example of a track deviating from route centerline.

C. Validation of the Data Filtering

For one subset of the collected data, the NATS data, audio recordings were available and analyzed by the data provider. For this subset of data, the results of the data filtering using ATC audio recordings were compared to the results from the filtering method applied by EUROCONTROL, using different thresholds for the automatic filter and with or without visual inspection as a final step. After each filtering process, the cross-track deviations of the remaining tracks from the reference trajectory were computed. Figure 5 shows the 1-cumulative distribution of these cross-track deviations for each filtering method. Note that the 1-cumulative distribution gives the probability of occurrence of the absolute value of a cross-track deviation greater than a certain value in the dataset. The data on the vertical axis in Figure 5 is presented using a logarithmic scale. The five distributions in Figure 5 were obtained using the following filtering techniques:

- automatic filter using a 0.5NM threshold without visual inspection of each track
- automatic filter using a 1NM threshold without visual inspection of each track
- automatic filter using a 1.5NM threshold without visual inspection of each track
- filtering based on the NATS ATC audio recordings
- automatic filter using a 1NM threshold and visual inspection of each track

Note that The shape of the distributions after solely automatic filtering looks typically different from the shapes of the distributions after filtering based on audio recordings or using the automatic process aided by visual inspection of each track. Therefore it was concluded that using only an automatic filter with a fixed threshold is not satisfactory. The combination of automatic filtering + visual inspection however generates a distribution with a shape that looks like the shape of the distribution filtered using the audio recordings, which can be seen by the green and red curves in Figure 5. The difference in probability of occurrence between the green and red curves in Figure 5 for a high cross-track deviation of 0.8NM is as follows: $8.2*10^{-6}$ for the EUROCONTROL filter using 1NM automatic threshold + visual inspection versus $2.8*10^{-5}$ for the filter based on audio recordings used by NATS. This yields a ratio of 2.8/0.82 = 3.4. It was concluded that the filtering method using the automatic filter with visual inspection was the best method under the absence of ATC audio recordings. It can be expected that the filtering method provides distributions which are slightly on the optimistic side though, as there is a risk that a visual inspection method deletes tracks which do not contain ATC interventions. It can also be observed in Figure 5 that a 1NM threshold for the automatic filter yielded a distribution which was missing the highest cross-track deviation of 1.1NM as observed in the distribution filtered using the ATC audio recordings. Therefore it was decided to put the threshold for automatic filtering of the tracks to 1.3NM either side of the reference route centerline. It was expected that this would provide the best compromise between filtering efficiency and accuracy.

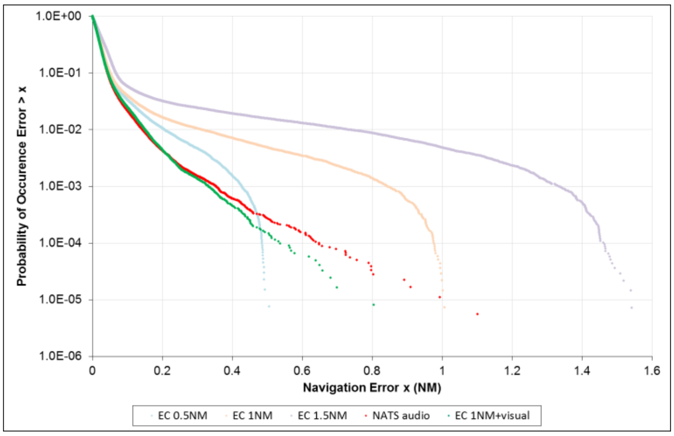


Figure 5. 1-cumulative cross-track error distributions of NATS data after different methods of filtering (logarithmic scale on vertical axis).

D. Computation of cross-track deviations

For the computation of cross-track deviations, the remaining tracks in the combined LVNL-DSNA-NATS dataset after filtering were subdivided in two categories: straight segments and turns segments. The start and end points of each turn segments were set equal to the start and end points of the fly-by transition area defined in RTCA DO-236C / EUROCAE ED-75D - “Minimum Aviation System Performance Standards (MASPS) - Required Navigation Performance for Area Navigation” [5]. The start and end point of the fly-by transition area are defined in this document by the maximum allowed turn radius, as follows:

$$\text{Max Radius} = (\text{Groundspeed})^2 / (g*\tan(\text{Bank Angle}))$$

with $g = 9.81\ m/s^2$ and Groundspeed and Bank Angle depending on altitude as explained below.

For low-altitude transitions:

- Groundspeed = 500kts
- Bank Angle = Min. of half the track change and 23°

For high-altitude transitions:

- Groundspeed = 750kts
- Bank Angle = 5°

In addition, turn initiation distance should be limited to 20NM from the turn waypoint.

Most aircraft execute the turn using a radius which is smaller than the maximum allowed turn radius. Theoretically this is allowed as long as their trajectory during the fly-by turn remains within the fly-by transition area, bounded by the maximum allowed turn radius defined in the MASPS. To assess the actual navigation performance during the turn, the actual turn radius was computed for each track at each turn waypoint in the dataset. Two methods were used for the computation of the actual turn radius:

- Simple method: this consisted in determining the point in the trajectory where the aircraft track was equal to the inbound track + ¼ of the track change and the point where the aircraft track was equal to the inbound track + ¾ of track change. With L the distance between these two points and θ the track change, the turn radius could then be estimated using the following formula:

$$\text{Radius} = L / (2*\sin(\theta/4))$$

- "Kasa" circle fitting method: a circle fitting method was used as described by I. Kasa in [6]. This method is a variant of the least square method and also required a conversion of the WGS-84 coordinates to a stereographic projection with the turn waypoint as origin.

Comparison of the two methods described above yielded that the simple method provided results which were satisfactory and accurate enough with less outliers than the "Kasa" method. Therefore, all further analysis was performed using the turn radius obtained by the simple method. After calculating the actual turn radius for all the tracks at a certain waypoint, the average turn radius was calculated for this waypoint and the turn segment was further subdivided into three subcategories:

- Pre-turn: the segment between the start point of the fly-by transition boundary and the start point of the arc defined by the average turn radius
- Mid-turn: the segment between the start and end points of the arc defined by the average turn radius
- Post-turn: the segment between the end point of the arc defined by the average turn radius and the end point of the fly-by transition boundary

Figure 6 illustrates an example of tracks abeam a turn waypoint "KOLIV". The reference route centerline, the fly-by transition boundary with start and end points and the arc defined by the average turn radius including start and end points are indicated. Most of the tracks in Figure 6 are well within the transition area and so is the arc defined by the average radius. A couple of tracks undershoot or overshoot the turn transition area.

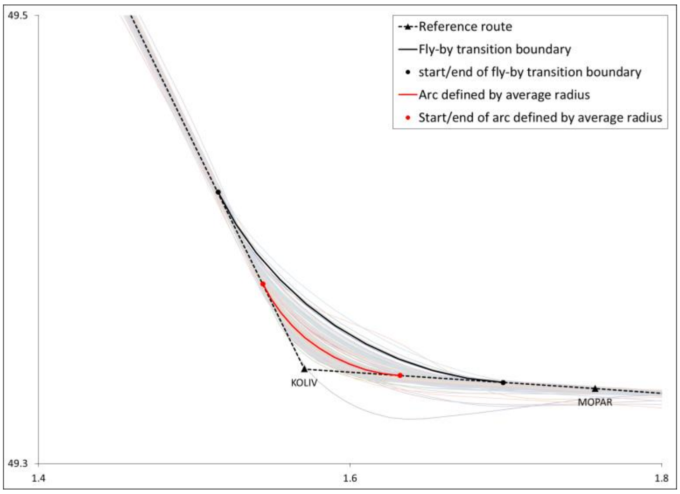


Figure 6. Example of tracks in a turn with indication of the fly-by transition boundary and the arc defined by the average radius.

For the computation of cross-track deviations in the three turn segment subcategories described above, the distance from the actual track was measured perpendicular to the original route centerline in the pre- and post-turn areas and perpendicular to the arc defined by the average radius in the mid-turn area. In the overall turn segment (consisting of the three subcategories), a cross-track deviation was computed for each recorded data point. Along straight segments, cross-track deviations were computed for data points separated by at least 1NM and maximum 2NM.

E. *Database size and fleet composition*

Table II lists the total number of tracks which were received from each ANSP as well as the number of tracks which were retained after filtering of the data.

TABLE II. NUMBER OF TRACKS BEFORE AND AFTER FILTERING

Source	No. of Tracks	No. of Tracks After Filtering	% Retained
NATS	12605	7237	57%
LVNL	131262	15333	12%
DSNA	434829	65529	15%
Total	**578696**	**88099**	**15%**

Table III provides an overview of the aircraft types contained in the combined LVNL-DSNA-NATS dataset after filtering, with associated number of tracks and data points for each aircraft type. Only the aircraft types responsible for 95% of the data points in the dataset are shown. The remaining aircraft types are grouped and listed as "Other". Note that these aircraft types represent the actual fleet anno 2014 which was operating at Amsterdam Schiphol airport (EHAM), London Heathrow airport (EGLL) and Paris Charles de Gaulle airport (LFPG).

TABLE III. FLEET COMPOSITION WITH NUMBER OF TRACKS AND NUMBER OF DATA POINTS AFTER FILTERING

AC Type	No. of Tracks	No. of Points
A320	15165	655173
A319	11614	516836
A321	6320	281809
B738	5761	272047
B77W	5243	208151
E190	4767	204262
A318	4521	195749
A332	4069	175083
B772	4139	163832
E170	3036	131478
A388	2253	88048
A343	1923	82767
B744	1818	78346
B763	2322	77861
RJ85	1618	69905
B737	1685	65852
A333	1451	58339
B752	1270	41308
F70	973	38385
B77L	857	35794
B733	689	27814
A346	823	27217
B739	576	24831
B788	605	22416
Other	4601	182021
Total	**88099**	**3725324**

Operations at EHAM require RNAV 1 approval as specified in the ICAO PBN Manual [3] since end 2012. The navigation specification for RNAV 1 requires GNSS or DME-DME sensors as an input to the navigation system. Fleet analysis reports provided by IATA and EUROCONTROL [7] indicate that the majority of the European fleet is equipped with GNSS nowadays.

F. Influence of Navigation Sensors

A mixture of navigation sensors can be expected to be installed on the aircraft in the overall dataset, including inertial systems with GPS and/or DME-DME updating. However, as the LVNL data sample contained call signs, it was possible to make a link with the EUROCONTROL Network Manager flight planning database and determine for which flights in the LVNL dataset, the availability of GNSS was indicated in the flight plan. In Table IV, the aircraft types which operated to or from EHAM and which did not have a GNSS capability indicated in the flight plan are listed, together with the number of tracks which were flown without GNSS and the total number of tracks (flown with or without GNSS) for each aircraft type. According to this analysis, in total 11% of the tracks in the LVNL dataset were flown with aircraft types which did not have GNSS indicated in the flight plan. Note that Table IV is the result of an analysis which was done using filed flight plan information. As it is commonly known, this information is not entirely error-free and therefore small errors can be in the data in Table IV. For example the appearance of Embraer E190 and E170 aircraft in Table IV can be questioned as it is very unlikely that these aircraft do not have GNSS.

Figure 7 provides the histogram of computed cross-track deviations in the LVNL dataset sample for straight segments (green) and mid turns (orange), for the procedures flown by aircraft equipped with GNSS. The vertical axis displays the frequency of occurrence of a certain cross-track deviation indicated on the horizontal axis. Figure 8 provides the same information but only for those procedures in the LVNL dataset which were flown by aircraft not equipped with GNSS. Obviously the histogram for the procedures flown without GNSS is slightly wider with a lower peak at the center. The standard deviations are respectively 0.056NM (straight segments) and 0.089NM (turns) for the cross-track deviations caused by aircraft with GNSS, while they are respectively 0.074NM (straight segments) and 0.140NM (turns) for the cross-track deviations caused by aircraft without GNSS.

TABLE IV. NUMBER OF TRACKS WITHOUT GNNS IN LVNL DATASET (ACCORDING TO FLIGHT PLAN DATA)

AC Type	No. of Tracks without GNSS	Total No. of Tracks	Tracks w/o GNSS / Grand Total
F70	967	973	6,3%
A320	396	1310	2,6%
F100	95	96	0,6%
B763	95	357	0,6%
B735	41	135	0,3%
B733	27	116	0,2%
B734	23	24	0,2%
B752	21	87	0,1%
A306	17	42	0,1%
All other types	25	12193	0,2%
Grand Total	**1707**	**15333**	**11,1%**

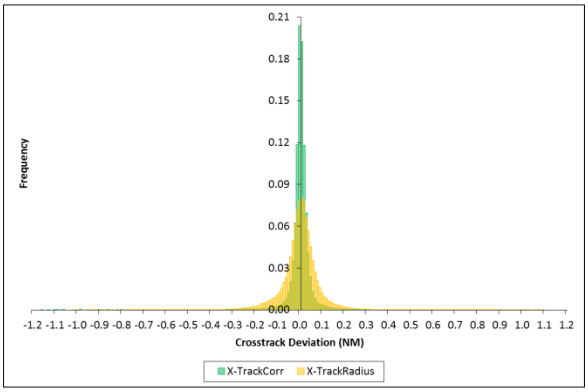


Figure 7. Histogram of cross-track deviations in LVNL data sample for straight segments (green) and mid turns (orange) for aircraft with GNSS.

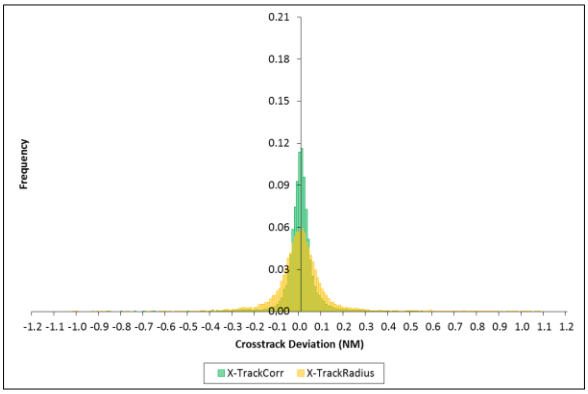


Figure 8. Histogram of cross-track deviations in LVNL data sample for straight segments (green) and mid turns (orange), for aircraft without GNSS.

III. Navigation Performance Distributions

When analyzing the lateral cross-track deviations in the combined LVNL-DSNA-NATS dataset, it was found that primarily, two factors influence the magnitude of the cross-track deviation: groundspeed and track angle change. In order to prepare for the computation of route spacings of parallel route configurations using the Collision Risk Model, the data of cross-track deviations was organized into the following 5 distributions:

- Combined LVNL-NATS-DSNA distribution, straight segments, high groundspeed (>350kts)
- Combined LVNL-NATS-DSNA distribution, straight segments, low groundspeed (<=350kts)
- Combined LVNL-NATS-DSNA distribution, turns with 30-60° track change, high groundspeed (>350kts)
- Combined LVNL-NATS-DSNA distribution, turns with 30-60° track change, low groundspeed (<=350kts)
- Combined LVNL-NATS-DSNA distribution, turns with 90° track change, low groundspeed (<=300kts)

Figures 9 to 18 illustrate the histograms and the 1-cumulative curves for the 5 categories of navigation performance distributions listed above. Note that the histogram provides the frequency of occurrence of a certain cross-track deviation in the dataset, while the 1-cumulative curve provides the probability of occurrence of the absolute value of a cross-track deviation greater than a certain value in the dataset.

Finally, Table V provides an overview of the most common statistical parameters of each of the 5 distributions, such as the sample size, mean, standard deviation, minimum and maximum values. Note that in Table V, the absolute value of the minimum or maximum values of the cross-track deviations in the dataset are in some cases slightly higher than 1.3NM, which was the threshold used in the automatic filter when processing the data. The reason for this is that the average value of the original cross-track deviations at each individual measurement point was sometimes not equal to zero, which indicates that there was in some cases a small bias in the data. There could be several reasons for this bias, one of them being the fact that the data originates from radar measurements. For distributions where there was a bias in the data, the bias was removed so that the average value of the cross-track deviations at each individual measurement point was zero.

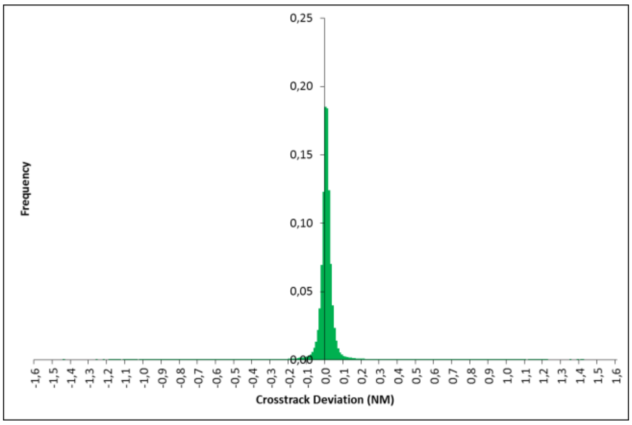


Figure 9. Histogram of Combined LVNL NATS DSNA distribution – Straight Segments – High GS (>350kts).

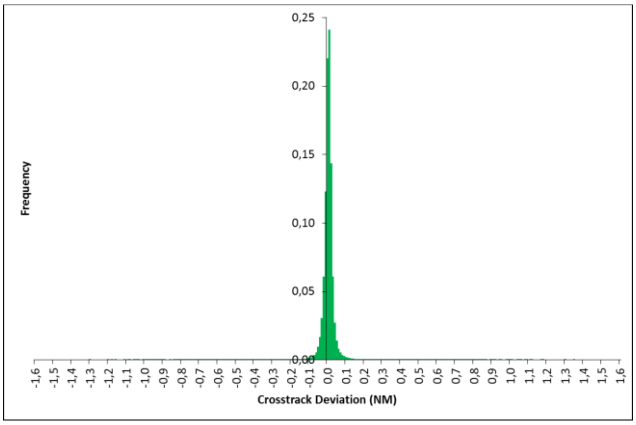


Figure 10. Histogram of Combined LVNL NATS DSNA distribution – Straight Segments – Low GS (<=350kts).

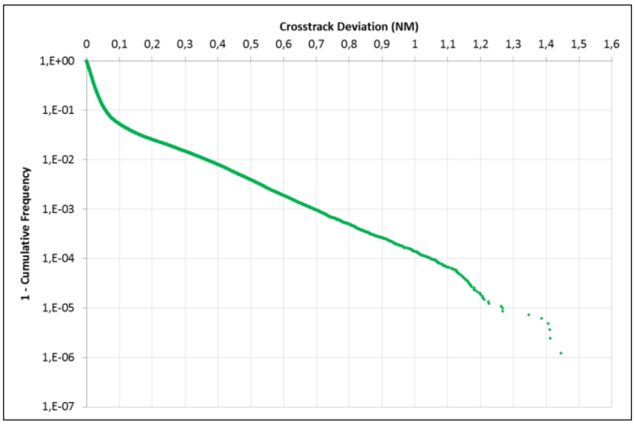


Figure 11. 1-Cumulative of Combined LVNL NATS DSNA distribution – Straight Segments – High GS (>350kts).

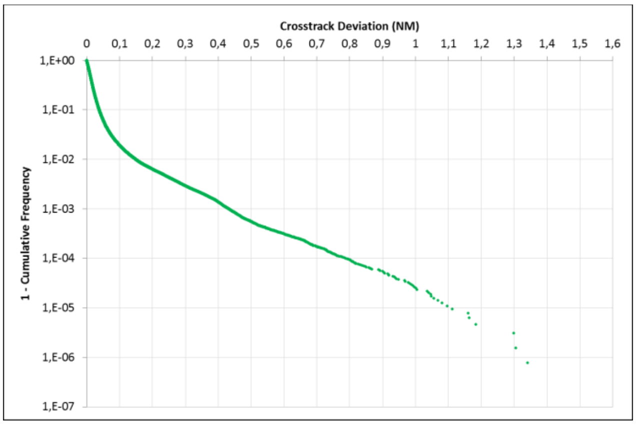


Figure 12. 1-Cumulative of Combined LVNL NATS DSNA distribution – Straight Segments – Low GS (<=350kts).

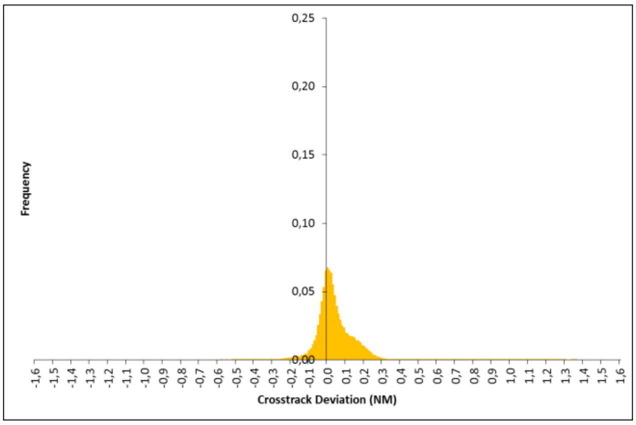


Figure 13. Histogram of Combined LVNL NATS DSNA distribution – Mid Turn 30-60° Track Change – High GS (>360kts).

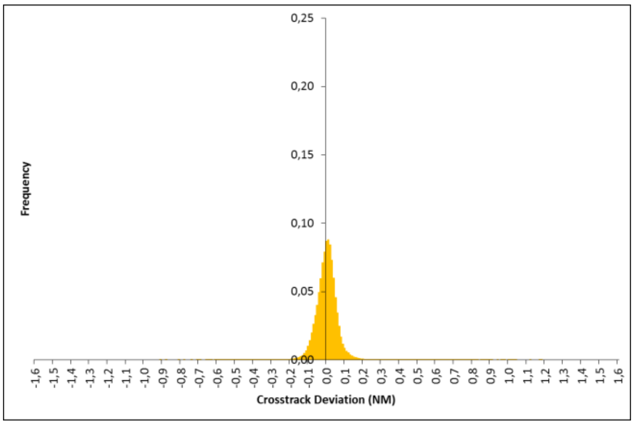


Figure 14. Histogram of Combined LVNL NATS DSNA distribution – Mid Turn 30-60° Track Change – Low GS (<=350kts).

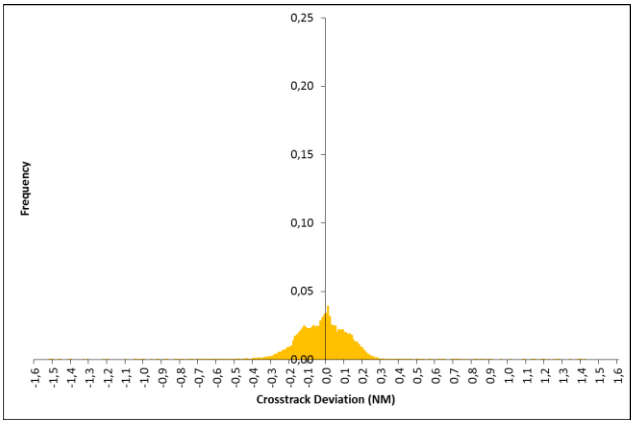


Figure 15. Histogram of Combined LVNL NATS DSNA SID distribution – Mid Turn 90° Track Change – Low GS (<300kts).

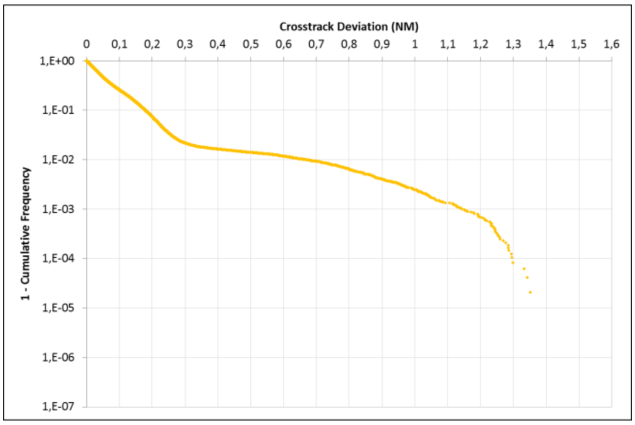


Figure 16. 1-Cumulative of Combined LVNL NATS DSNA distribution – Mid Turn 30-60° Track Change – High GS (>360kts).

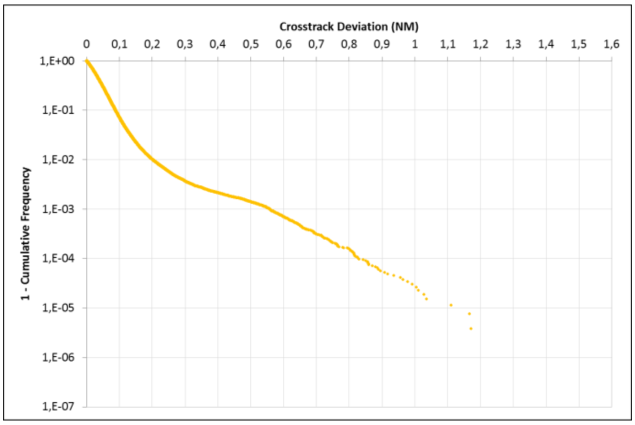


Figure 17. 1-Cumulative of Combined LVNL NATS DSNA distribution – Mid Turn 30-60° Track Change – Low GS (<=350kts).

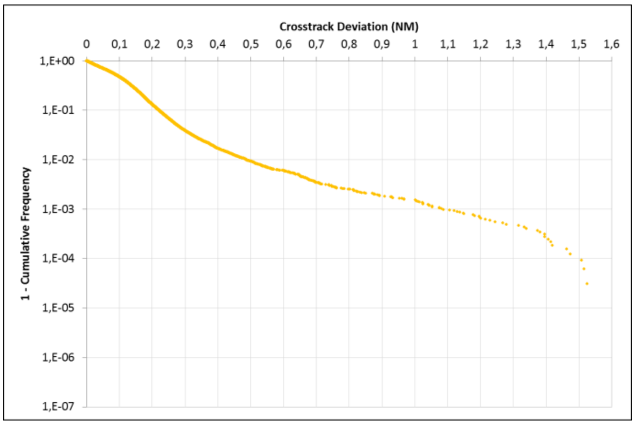


Figure 18. 1-Cumulative of Combined LVNL NATS DSNA SID distribution – Mid Turn 90° Track Change – Low GS (<300kts).

TABLE V. DISTRIBUTION PARAMETERS

	No. of data points	Cross-track deviations (NM)			
		Mean	StdDev	Min	Max
Straight Segments High GS (>350kts)	825264	0,00	0,07	-1,45	1,41
Straight Segments Low GS (<=350kts)	1297549	0,00	0,04	-1,31	1,34
Mid Turn 30-60° High GS (>350kts)	48672	0,04	0,13	-0,59	1,35
Mid Turn 30-60° Low GS (<=350kts)	267099	0,00	0,06	-0,92	1,17
SID Mid Turn 90° Low GS (<300kts)	32579	-0,03	0,15	-1,53	1,42

IV. COLLISION RISK MODELING

A conventional parallel route Collision Risk Model was used for the computations of route spacings and associated risks for a set of sample parallel route configurations presented further below in Table VIII. A detailed report of the Collision Risk Modeling (CRM) supporting this work, is given by G. Moek in [8]. The basic principle is summarized below. The equation used in the Collision Risk Model is as follows:

$$N_{ay} = P_{ATC}(S_y)P_{xz}P_y(S_y)\left[\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z}\right]$$

The meaning of the various parameters in this equation is explained in Table VI, while the quantities of the parameters used in the collision risk modeling of the sample parallel route configurations are provided in Table VII.

TABLE VI. DEFINITION OF PARAMETERS IN COLLISION RISK MODEL

Quantity	Description
N_{ay}	Expected number of fatal accidents per flight hour due to the loss of lateral separation on parallel routes in radar airspace
$P_{ATC}(S_y)$	Probability of ATC intervention failure as a function of the spacing S_y between parallel routes in radar airspace
P_{xz}	Probability of joint longitudinal and vertical overlap for aircraft on parallel routes in radar airspace
$P_y(S_y)$	Probability of lateral overlap for aircraft on parallel routes due to loss of lateral separation resulting from lateral navigation performance of PBN aircraft and flight crew
V_x	Average value of the absolute relative longitudinal speed between two aircraft (possibly subdivided into same- and opposite-direction traffic)
V_y	Average value of the absolute relative lateral speed between two aircraft
V_z	Average value of the absolute relative vertical speed between two aircraft
λ_x	Average aircraft length
λ_y	Average aircraft width
λ_z	Average aircraft height

TABLE VII. COLLISION RISK MODEL PARAMETER VALUES

Parameter	Value	
	En-route airspace	Terminal airspace
$P_y(S_y)$	See G. Moek [8]	
$P_{ATC}(S_y)$		
Flow rate (ac per flight level per hour)	15	30
P_x	1.477×10^{-3}	3.940×10^{-3}
P_z	0.367	0.076
P_{xz}	5.419×10^{-4}	2.995×10^{-4}
V_x (opposite direction)	900 kts	440 kts
V_x (same direction)	35 kts	26 kts
V_y	43 kts	32 kts
V_z	1.5 kts	1.5 kts
λ_x	0.022 NM	0.022 NM
λ_y	0.020 NM	0.020 NM
λ_z	0.0063 NM	0.0063 NM

The lateral overlap probability $P_y(S_y)$ was determined for each of the sample parallel route configurations based on the convolution of two functions which were used to model the 1-cumulative distributions presented in Figures 11, 12, 16, 17 and 18. The mathematical models which were fitted to the 1-cumlative distributions were either a Gaussian-Double Exponential (GDE), or a Double-Double Exponential (DDE) model. Figure 19 provides an example of a Double-Double Exponential (DDE) function used to fit the combined LVNL-NATS-DSNA distribution for straight segments and high groundspeeds (>350kts).

The ATC intervention failure probability $P_{ATC}(S_y)$ is given by G. Moek in [8]. Note that in [8], the ATC intervention failure probability $P_{ATC}(S_y)$ is given as a function of the route spacing S_y for both en-route and terminal airspace.

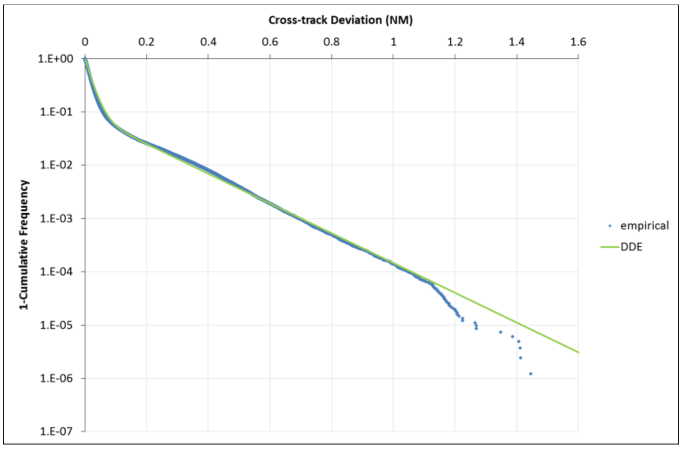


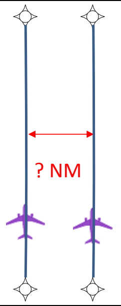
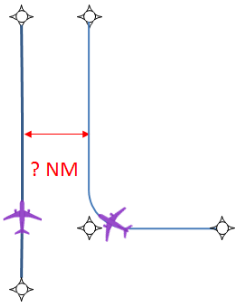
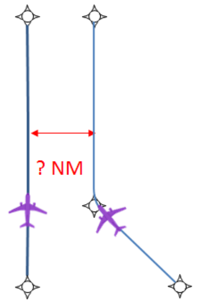
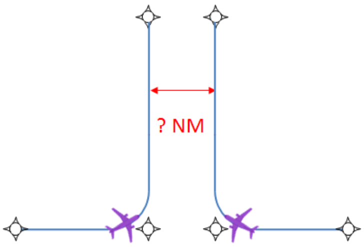
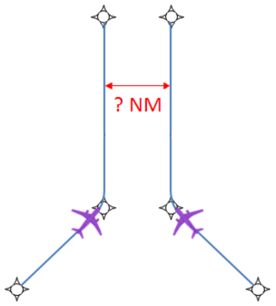
Figure 19. Example of a Double-Double Exponential (DDE) function used to fit the combined LVNL NATS DSNA distribution – Straight Segments – High Groundspeed (>350kts)

V. ROUTE CONFIGURATIONS & SPACING EXAMPLES

Table VIII provides examples of specific parallel route configurations which were evaluated using the Collision Risk Model (CRM). The Navigation Performance distributions used, as well as the assumed Target Level of Safety are indicated above each route configuration. Table VIII lists the computed risk (indicated as $N_{ay\text{-}best}$ for the best estimate) for a given route spacing and assumed average groundspeed (indicated as GS) in a specific route configuration. The route spacings used in the CRM were chosen such that they are not below the radar separation minima (assumed to be 3NM in the extended terminal area) and such that they provide a risk below the Target Level of Safety, indicated as TLS in Table VIII.

Lateral collision risk for the merging route configurations has been calculated by means of the conventional parallel route CRM. The probability of lateral overlap has been calculated by means of the straight-segment lateral deviation distribution for the aircraft on a straight route and in case of a merging or converging routes by means of the mid-turn lateral distribution for the pertinent turn angle.

TABLE VIII. Sample Route Configuration with Target Spacing and Risk Computed using CRM

Route Configuration	Description	Sample route spacings and risks based on the Collision Risk Model
1. Parallel tracks. Same direction (Both AC in level flight).		Combined LVNL, NATS, and DSNA straight-segment data Applicable TLS: 4 x 10^{-9} fatal accidents per flight hour (f.a.f.h.) GS 450kts Spacing used in CRM: 3 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 3.69 \times 10^{-11}$ (f.a.f.h.) GS 220kts Spacing used in CRM: 3 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 1.07 \times 10^{-11}$ (f.a.f.h.)
3. Merging Tracks. Joining a parallel path with a 90° fly-by turn. Both AC in level flight.		Combined LVNL, NATS, and DSNA straight segment and 90 degree turn angle data Applicable TLS: 4 x 10^{-9} fatal accidents per flight hour (f.a.f.h.) GS 220kts Spacing used in CRM: 5 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 3.78 \times 10^{-10}$ (f.a.f.h.)
4. Merging tracks. Joining a parallel path with a 45° fly-by turn. Both AC in level flight.		Combined LVNL, NATS, and DSNA straight segment and 30 – 60 degree turn data Applicable TLS: 4 x 10^{-9} fatal accidents per flight hour (f.a.f.h.) GS 450kts Spacing used in CRM: 4 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 2.34 \times 10^{-10}$ (f.a.f.h.) GS 220kts Spacing used in CRM: 4 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 6.68 \times 10^{-11}$ (f.a.f.h.)
5. Converging tracks. Both aircraft at same level and in same direction with 90° fly-by turns.		Combined LVNL, NATS, and DSNA 90 degree turn angle data Applicable TLS: 4 x 10^{-9} fatal accidents per flight hour (f.a.f.h.) GS 220kts Spacing used in CRM: 5 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 8.37 \times 10^{-10}$ (f.a.f.h.)
6. Converging tracks. Both aircraft at same level and in same direction with 45° fly-by turns.		Combined LVNL, NATS, and DSNA 30 – 60 degree turn data Applicable TLS: 4 x 10^{-9} fatal accidents per flight hour (f.a.f.h.) GS 450kts Spacing used in CRM: 4 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 6.61 \times 10^{-10}$ (f.a.f.h.) GS 220kts Spacing used in CRM: 4 NM **(see Key Points 1, 2 and 3)** $N_{ay-best} = 1.39 \times 10^{-10}$ (f.a.f.h.)

Numerous real-time simulations undertaken over the past ten years for RNAV 1, RNP 1 and Advanced RNP [3] as well as practical implementations following an implementation safety case, have indicated that operationally, achievable route spacings are greater than the radar separation minima [4]. For example, when the minimum radar separation is 3 NM, route spacings of 4-5 NM have been achieved. Similarly, when the minimum radar separation is 5 NM, route spacings of 6-7 NM have been achieved. Therefore, when reading Table VIII, attention is drawn to the following three key points:

- **Key Point 1**: A limitation of using radar surveillance as a mitigation of risk is that the spacing between two routes cannot be the same or less than the radar separation minima. This is because a lateral deviation could instantly cause a separation infringement. As such, allowing for sufficient time for the controller to detect and correct a deviation and for the pilot to respond correctly has tended to convert into at least a minimum of 4-5 NM route spacing in an environment using 3NM radar separation minima.

- **Key Point 2**: No published spacing results for continental application (or study supporting these results) can be considered universal norms. Results are valid only for the assumptions and data used, the particular operating environment and airspace and operational concept envisaged. It is also stressed that route spacing values supported by extensive data analysis, mathematical modeling and airspace design do not in itself ensure that the aircraft will adhere to the route to ensure that the route spacing is maintained. Critical to successful flight operations are procedure design, the proper coding of routes in aircraft databases, flyability checks, etc.

- **Key Point 3**: The resolution of the radar display (a function of ATC sector size) has very clearly become a determining human factor which forms part of the post-CRM implementation safety analysis to determine the acceptable (final) route spacing. To be included in these considerations are items such as label size and algorithm affecting label orientation both of which affect the potential for label overlap, as well as the aircraft 'target' size and so forth.

VI. CONCLUSION

Navigation performance distributions computed from data consisting of 88,099 tracks collected during 1 year from aircraft flying into Amsterdam, Paris Charles De Gaulle and London Heathrow indicate that actual lateral navigation performance nowadays is outstanding. The 95% lateral navigation Total System Error is in the order of magnitude of 0.14NM and 0.08NM from the route centerline for straight tracks with respectively high groundspeeds (above 350kts) and low groundspeeds (below 350kts). For fly-by turns the lateral navigation error was computed from a reference centerline defined by an average turn radius which was calculated for each turn point in each procedure in the dataset. The lateral navigation Total System Error in turns depended on the track change and the groundspeed. For low groundspeeds and turns with a track change of about 90 degrees, the 95% lateral navigation Total System Error was about 0.3NM. An analysis was also performed using a subset of the total dataset from which indications were available about the position sensors the aircraft had been using. A comparison was made been the performance of aircraft equipped with and without GNSS. For the aircraft without GNSS (typically navigating with inertial systems and DME-DME signals) the 95% lateral navigation Total System Error was about 0.15NM along straight segments and 0.28NM in turns. The latter values were computed for all groundspeeds and turn angles in the data subset.

The lateral performance distributions were fed into a Collision Risk Model which was used to compute the collision risk for a set of route configurations consisting of parallel routes, as well as merging and converging tracks with different track change angles. For parallel routes it was found that a route spacing of 3NM would meet the target level of safety, taking into account the observed aircraft performance which was made available through the data collection and analysis. Merging and converging tracks using fly-by turns required route spacings between 4 and 6NM depending on the track change angle and the groundspeed, to obtain a risk of the same order of magnitude as for the straight tracks

Overall this study has demonstrated that using the new navigation performance data, navigation performance is not the prevalent factor anymore the determination of route spacing in a radar environment. With increased navigation performance, radar separation minima (e.g. 3NM in the terminal area and 5NM en-route) and human factors such as the controller's screen resolution and ATC sector size are the more dominant elements to be taken into consideration for the determination of route spacing minima.

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DISCLAIMER

This work was done under the auspices of the Network Manager, a centralized function nominated by the European Commission to EUROCONTROL in 2011 [9]. The material contained in this paper is the sole opinion of the authors and in no way represents an official statement or position of the Network Manager.

REFERENCES

[1] EUROCONTROL, European Airspace Concept Handbook for PBN Implementation, Edition 3.0, 2013

[2] EUROCONTROL Experimental Centre, "Navigational Accuracy of Aircraft Equipped with Advanced Navigation Systems, Final Report", Report No. 216, EUROCONTROL, June 1988.

[3] International Civil Aviation Organisation, "Performance Based Navigation (PBN) Manual", ICAO Doc 9613, Fourth Edition, 2013.

[4] EUROCONTROL, "Advanced Required Navigation Performance (A-RNP) Real-Time Simulation – Final Report", April 2010

[5] RTCA Special Committee 227 and EUROCAE Working Group 85, "Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation", RTCA DO-236C / EUROCAE ED-75C, 2013.

[6] I. Kasa, "A circle fitting procedure and its error analysis", IEEE Transactions on Instrumentation and Measurement, March 1976.

[7] International Air Transport Association (IATA), "Avionic Equipage Survey", Miami, Florida, 2012.

[8] G. Moek, "Update to Deliverable D3 – Determination of Horizontal Overlap Probability, Lateral Collision Risk and Identification of Appropriate Spacing Minima", NLR Air Transport Safety Institute, September 2016.

[9] https://www.eurocontrol.int/network-manager